Booker, J., North, D., Yon, J., & Mellor, P. (2019). Generator Configuration for a Helicopter Quadruplex Electric Tail Rotor. *Journal of Engineering*, *2019*(17), 4471-4474 . https://doi.org/10.1049/joe.2018.8233

The Journal of Engineering

The 9th International Conference on Power Electronics, Machines and Drives (PEMD 2018)

Generator configuration for helicopter quadruplex electric tail rotor

eISSN 2051-3305
Received on 26th June 2018
Accepted on 30th July 2018
doi: 10.1049/joe.2018.8233
www.ietdl.org

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Abstract: With the move to more electric aircraft (MEA), a key area of investigation is the development of commercially viable systems which are reliable, efficient, low mass, and are compatible and commensurate with the power and multiplex requirements of current and future aircraft. In rotorcraft, the pace of adopting more electric systems, to replace conventional mechanical and hydraulic ones, say, is perceived as being much lower than in fixed wing aircraft. However, recently there has been growing evidence to suggest that a quadruplex electric tail rotor (ETR) is a technically viable solution. This paper shows the methodology to support the most reliable configuration of the four independent generators required to power such a quadruplex tail rotor drive, and takes account of the failure severity due to power loss in each independent channel, target reliability setting, and supporting reliability analyses. The conclusions drawn support a particular hybrid series-parallel configuration of generators, with identification of further work related to the gearbox reliabilities which support the reliability attainment for the configuration.

1 Introduction

The development of the more electric aircraft (MEA) has, until recently, primarily focussed on the electrification of non-propulsive aerospace systems. Through this process, functions such as environmental control, engine start, and flight surface actuation, traditionally powered by hydraulic or pneumatic sources, are being implemented electrically. This evolution has been most prevalent in the fixed-wing sector and is expected to convey several benefits in particular reduced maintenance costs, and recued fuel burn. However, to achieve complete electrification of an aircraft's auxiliary systems, further innovation is required in power conversion technology, such as improved power density, increased reliability and advances in fault tolerance. It is also perceived that the more traditional power systems fail more gradually than electrical machines, where in the latter, a sudden loss of power could be experienced, therefore, the introduction of multiplex systems is also crucial to improve reliability of electrical power systems on aircraft, but potentially with the disadvantages of adding more mass, cost, and complexity [1].

Recently, a clean sky green rotorcraft (GRC) program, funded by the European Union, has investigated the technical viability of powering the tail rotor of a helicopter using an electric drive. This replaces the mechanical transmission and gearbox arrangement currently employed [2]. This electric tail rotor (ETR) system has a quadruplex fault tolerant configuration and comprises four independently controlled power channels which share load evenly during normal operation. The removal of direct mechanical coupling from the main rotor offers new modes of operation, for example, variable tail rotor speed can be achieved independent of the main rotor for increased manoeuvrability under certain flight conditions. Although not a propulsion system outright, ETR represents a major advancement in more electric rotorcraft [3]. Traditionally, rotorcraft have had very low levels of installed electric power, primarily serving avionics and wing ice protection systems. The ETR project is currently at the ground testing phase [4].

The feasibility of the ETR concept is dependent upon the availability of a weight compatible source of electrical power generation, and for a quadruplex drive, four independent channels of power must be configured on board the helicopter. The current capacity of electrical power generation on existing rotorcraft is far below that required by an ETR system (~200 kW), and the state-of-the-art wound field generators used in fixed wing applications are not necessarily suited to the high-vibration environment found on rotorcraft. High-speed surface-mounted PM (SMPM) machines are being increasingly investigated for direct-drive generators such as this. They have great potential for high reliability, compactness, low weight, high efficiency, high power density, low acoustic noise, and low maintenance costs In this project, a continuously rated 50 kW SMPM generator has been designed to withstand harsh rotorcraft environmental conditions, while providing robust and reliable performance typical of permanent magnet (PM) electrical machines. The cooling and lubrication has also been designed to integrate with the existing oil circuit for the main rotor gearbox and meets the on-board electrical specification of existing rotorcraft.

Here, a methodology is presented for defining the most appropriate configuration of the four generators for a quadruplex ETR drive. The objective is to minimise the footprint of the installation, and its complexity, while attaining maximum reliability of the system.

2 Methodology

2.1 System reliability theory

Reliability can be defined as the ability of a component, or system of components, to perform their required function under the stated conditions, for a specified period of time. The equations to predict the reliability of a system of components, such as series and parallel as shown in Fig. 1, are provided in (1) and (2), respectively [5].

$$R_{\text{sys(series)}} = R_1 \times R_2 \times R_3 \times \dots R_n \tag{1}$$

$$R_{\text{sys(parallel)}} = 1 - (1 - R_i)^n \tag{2}$$

where R_{sys} = reliability of the system; n = number of components; R_{i} = reliability of ith component (of the same reliability) in a system; $R_{1,2,\dots \text{n}}$ = reliability of independent components.

A ‘k-out-of-n’ reliability assessment is often used for redundancy evaluation in fault-tolerant systems i.e. not all components in the system are operational [6]. The reliability of the system with redundancy is provided in (3):

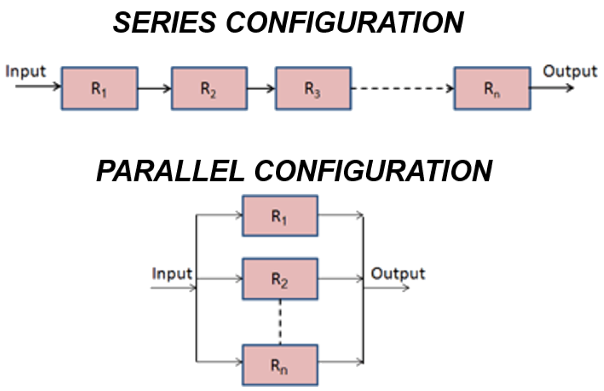


Fig. 1 *Series and parallel components in a system*

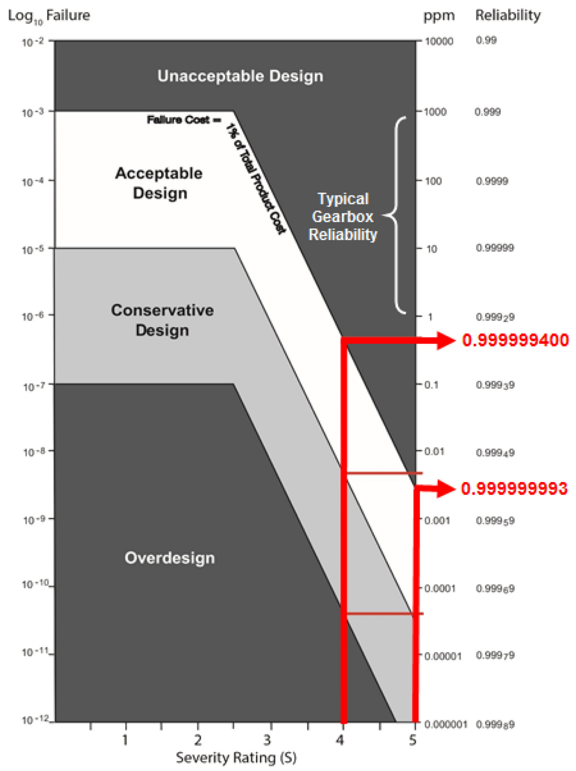


Fig. 2 *Reliability map based on FMECA severity ratings (target reliabilities shown at severity rating (S) = 4 and 5)*

Catastrophic – sudden loss of primary subsystem function with direct safety implications/ effects on helicopter platform	5	**Loss of 4 out of 4 (0% power available)** **Loss of 3 out of 4 (25% power available)**
Severe – sudden loss of primary subsystem function with potential safety effects on helicopter platform only with secondary subsystem failure effects	4	**Loss of 2 out of 4 (50% power available)**
Major – gradual failure. Subsystem operable but at reduced level of performance, directly effecting functionality. No immediate effect on helicopter platform safety in service	3	**Loss of 1 out of 4 (75% power available)**
Minor – failure resulting in minor implications to performance in subsystem function, with no safety implications to helicopter system	2	
Insignificant – no failure effect on subsystem performance, functionality or safety effect on helicopter platform	1	

Fig. 3 *FMECA severity ratings (S) for a quadruplex ETR system for loss of power channels*

$$R_{\text{sys(Redundancy)}} = \sum_{r=k}^{n} \binom{n}{r} R_C^r (1 - R_C)^{n-r} \quad (3)$$

where R_C = reliability of component (of the same reliability); k = minimum number of components in system for operation.

From these equations, any configuration of components can be analysed in terms of overall system reliability; or having set a target reliability for the system, provide the component reliabilities.

2.2 Setting target reliabilities

For any reliability prediction methodology to be practical, a decision must be made as to the reliability target appropriate for the application [7]. An appreciation of the severity of failure consequence together with failure probability i.e. risk would be useful because components and systems need to be more reliable in safety critical cases. Research into the effects of non-conformance and associated costs of failure found that an area of acceptable design can be defined for failure occurrence versus severity of consequence [8].

Here, there are the two elements of risk – Occurrence, or how many times do we expect the failure to occur? – and severity, what are the consequences? In very complex systems, severe consequences can result from the failure of a single component. The implication is that reliability of the system is relatively insensitive to the number of components, and, therefore, their configuration and the reliability is determined by their weakest link. If the weakest component can endure the most severe duty without failing, the system will be completely reliable. This assumption forms the basis of target reliability selection against which each configuration will be assessed later. Target reliabilities should also be set to achieve minimum failure cost [9].

From these arguments, acceptable limits of failure probability relative to a FMECA (Failure Mode, Effects, and Criticality Analysis) Severity (S) Scale from 1 (little or no effect) to 5 (catastrophic consequence) can be drawn on a Reliability Map, as shown in Fig. 2 [8, 10]. The map includes areas associated with acceptable, unacceptable, conservative, and overdesign. The overdesign area is probably not as important as the minimum reliability for a particular severity rating, but does identify possible wasteful and costly designs. The integrated use of FMECA in the setting of reliability targets utilises information from an already well utilised technique in industry; with ∼70% of companies using it in the UK to identify potential failure modes and prioritise risk [11].

Using the reliability map to set targets is also shown on Fig. 2, for example, for Severity Ratings (S) = 4 and 5, where:

- Severity Rating (S) = 4; $R_{sys} > 0.9999994$;
- Severity Rating (S) = 5; $R_{sys} > 0.999999993$.

Focusing on the application here, the Severity Rating (S) from 1 to 5, for the loss of independent power channels (loss of one, two and three generators), was agreed through a team-based exercise with all stakeholders, and the definitions and results are shown in Fig. 3. The loss of two or three, out of the four generators, in terms of power delivery, has a severe or catastrophic consequence on the flight stability of the helicopter, while the loss of one generator is tolerable.

2.3 Generator configurations

In developing a reliable system, a number of design schemes should be generated to explore each for their ability to meet the target reliability. Several schemes, or configurations, of generator are considered to be possible in the specification envelope for the target helicopter platform (see Fig. 4). These are: all in series (e.g. on a common shaft), all in parallel, and parallel-series (two parallel channels of two generators in series). The second and third configurations need to be evaluated together with a splitter gearbox and all three together with a Central Control Unit (CCU) (not included in the analysis), but that is not considered here. Each configuration needs to be assessed to meet a target system reliability, as described in Section 2.2.

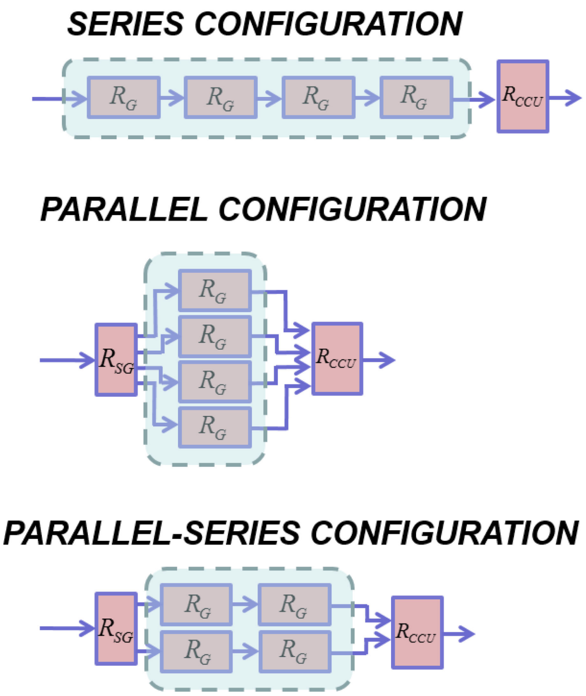


Fig. 4 *Generator configurations (where: R_{SG} = splitter gearbox reliability, R_G = generator reliability, R_{CCU} = central control unit reliability)*

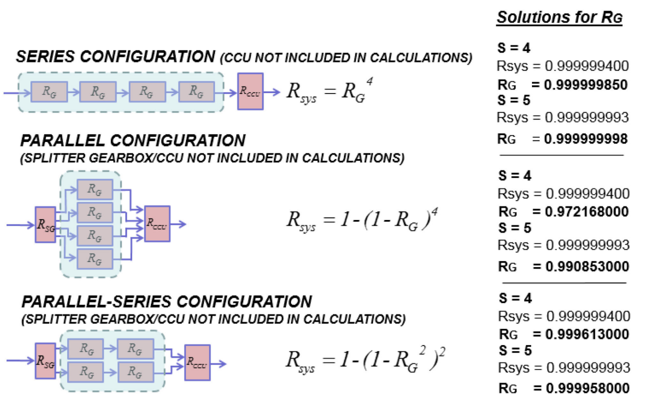


Fig. 5 *Basic generator reliabilities for each configuration*

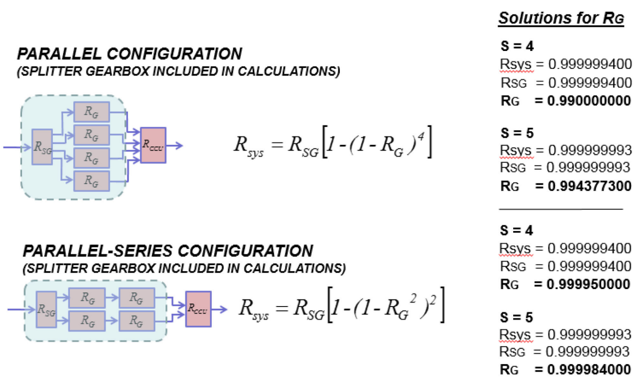


Fig. 6 *Basic generator reliabilities for configurations including the splitter gearbox*

3 Analysis and results

Several assumptions are used in the analysis of the generator configurations:

- The output shaft from the main gearbox is considered to be intrinsically reliable, R ≈ 1.
- The output shaft from the main helicopter gearbox will need to be split – hence a 'splitter gearbox' immediately before the bank of four generators in the different configurations, other than series one.
- Each generator has the same reliability and is independent from the others.
- The system reliability targets are a minimum.
- Initially, the study looks at generator reliabilities needed for different system configurations, then a system which is operational only with two out of four generators working (k out of n system).

Fig. 5 shows the analysis of each configuration in terms of its ability to meet a target system reliability, based on Severity Ratings (S) 4 and 5, and the subsequent generator reliability needed to meet the system reliability. Note, at this stage, no account is taken of the splitter gearbox needed, as a baseline evaluation. It is clear, understandably, that the series configuration requires generator probability of failure of two parts in a billion in order to function with all four generators providing power. The generator reliabilities relax somewhat for the other configurations and are far more realisable in practice.

In Fig. 6, the inclusion of the splitter gearbox for the two configurations requiring it is included. For the fully parallel configuration, a four-way split is needed; whereas for the parallel-series hybrid configuration, a two-way split from the main rotor gearbox shaft is required. In order to solve for the generator reliability, the splitter gearbox reliability needs to be of the same reliability as the whole system, the validity of which will be commented on later. The inclusion of a series gearbox has a marginal impact on the generator reliabilities required for each severity rating-based target, as you would expect given the assumed high reliability, and is useful for model building (the CCU reliability can be added in the same way if known). It also shows that even with a splitter gearbox of high reliability, up to 2% improvement in generator reliability is required to main system reliability targets.

Fig. 7 shows the results for the 'k out of n' analysis for Severity Rating (S) = 4, where two out of the four channels have been lost on a purely parallel configuration. Fig. 8 shows the same situation, but for the parallel-series configuration where '1 out of 2' channels is lost (equivalent to '2 out of 4' for this configuration). The solutions to the equations are through iteration, and no splitter gearbox in series is included at this stage. Comparing the generator reliabilities needed to meet the system target, the generator for the parallel configuration approaches unity, compared to a more attainable value for the hybrid configuration. There is the additional requirement of a four-way splitter gearbox for the purely parallel configuration, and so this configuration looks more unlikely as a final system.

Finally, a parallel-series configuration is considered, with Severity Rating (S) = 4, but with the inclusion of a splitter gearbox in series. The reliability of each generator approaches unity due to the reliability of the splitter gearbox, even though it was set at the system reliability target (see Fig. 9).

4 Conclusions

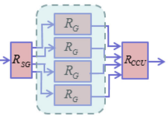
The methodology, model development, and key results from a system reliability approach to analyse the most favourable configuration of generator for a future quadruplex ETR has been discussed. This included a reliability target setting approach based on failure mode/severity, and the application of reliability analyses for redundant systems, for quadruplex systems.

In summary, the parallel-series (hybrid) configuration of generators has been found to be the most promising in terms of meeting reliability targets for such a system and occupies a low footprint within the helicopter platform – not overly long like a series system, or overly wide like parallel system of generators.

However, an individual generator reliability, $R_G > 0.999999$, even for the Severity Rating (S) = 4 case, is still difficult to verify at this stage whether it is attainable (equates to 1 part per million failure rate). A priority direction for the work is to evaluate the

PARALLEL CONFIGURATION
(SPLITTER GEARBOX/CCU NOT INCLUDED IN CALCULATIONS)

Severity (S) = 4
Rsys = 0.999999400



$$R_{sys} = \sum_{r=k}^{n} \binom{n}{r} R_G^{\,r} (1 - R_G)^{n-r}$$

$$0.9999994 = \sum_{r=k}^{n} \binom{4}{2} R_G^{\,r} (1 - R_G)^{4-3}$$

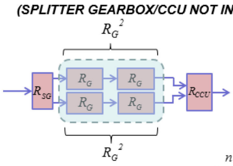
$$0.9999994 = \binom{4}{2} R_G^{\,2} (1 - R_G)^2 + \binom{4}{3} R_G^{\,3} (1 - R_G)^1 + \binom{4}{4} R_G^{\,4} (1 - R_G)^0$$

$R_G \approx 1$ (Cannot guarantee generator intrinsically reliable. 1→4 drive splitter gearbox is in series, so weaker link)

Fig. 7 *k out of n System reliability (2 out of 4) for parallel configuration of generators*

PARALLEL-SERIES CONFIGURATION
(SPLITTER GEARBOX/CCU NOT INCLUDED IN CALCULATIONS)

Severity (S) = 4
Rsys = 0.999999400



$$R_{sys} = \sum_{r=k}^{n} \binom{n}{r} \left[R_G^{\,2}\right]^r \left(1 - R_G^{\,2}\right)^{n-r}$$

$$0.9999994 = \sum_{r=k}^{n} \binom{2}{1} \left[R_G^{\,2}\right]^r \left(1 - R_G^{\,2}\right)^{2-1}$$

$$0.9999994 = \binom{2}{1} \left[R_G^{\,2}\right]^1 \left(1 - R_G^{\,2}\right)^1 + \binom{2}{2} \left[R_G^{\,2}\right]^2 \left(1 - R_G^{\,2}\right)^0$$

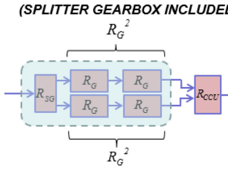
$$R_G^{\,2} = 0.999999$$

$R_G = 0.99999945$ (Generator reliability is comparable with system reliability target. 1→2 drive splitter gearbox is in series, so still weaker link)

Fig. 8 *k out of n System reliability (1 out of 2) for parallel-series configuration of generators*

PARALLEL-SERIES CONFIGURATION
(SPLITTER GEARBOX INCLUDED IN CALCULATIONS)

Severity (S) = 4
Rsys = 0.999999400
RSG = 0.999999400



$$R_{sys} = R_{SG} \left[\sum_{r=k}^{n} \binom{n}{r} \left[R_G^{\,2}\right]^r \left(1 - R_G^{\,2}\right)^{n-r} \right]$$

$$0.9999999 = \sum_{r=k}^{n} \binom{2}{1} \left[R_G^{\,2}\right]^r \left(1 - R_G^{\,2}\right)^{2-1}$$

$$0.9999999 = \binom{2}{1} \left[R_G^{\,2}\right]^1 \left(1 - R_G^{\,2}\right)^1 + \binom{2}{2} \left[R_G^{\,2}\right]^2 \left(1 - R_G^{\,2}\right)^0$$

$$R_G^{\,2} \approx 1$$

$R_G \approx 1$ (Cannot guarantee generator intrinsically reliable)

Fig. 9 *k out of n System reliability (1 out of 2) for parallel-series configuration of generators, with splitter gearbox*

reliabilities of additional (splitter) gearboxes, compared to the effort of redesigning the main rotor gearbox to have two independent variable speed output shafts (one currently, which has the purpose of mechanically driving the tail rotor through a gearbox). Typically, gearbox reliabilities range from ∼0.999 to ∼0.999999 [12], and, therefore, could be a weak link in the proposed configuration of generators to power ETR. The exclusion of gearboxes, as far as possible, is needed to meet system-level reliability targets. Generator reliabilities are marginally better than gearboxes in terms of failure rate, but still the expectation is that generator reliabilities equivalent to <1 part in a million will be required.

5 Acknowledgments

The authors are grateful to the industrial collaborator, Leornardo Helicopters, Yeovil, UK, for the funding of this research, and in particular Keith Stickels and Martin Barber are thanked for their contribution.

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